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Materials Science and Technology
Nanoscience

Fabrication of Large-Area 3D Nanostructures

Proximity-field nano-patterning lithography can produce nanostructures over large areas using a simple optic and a single cycle of lithography

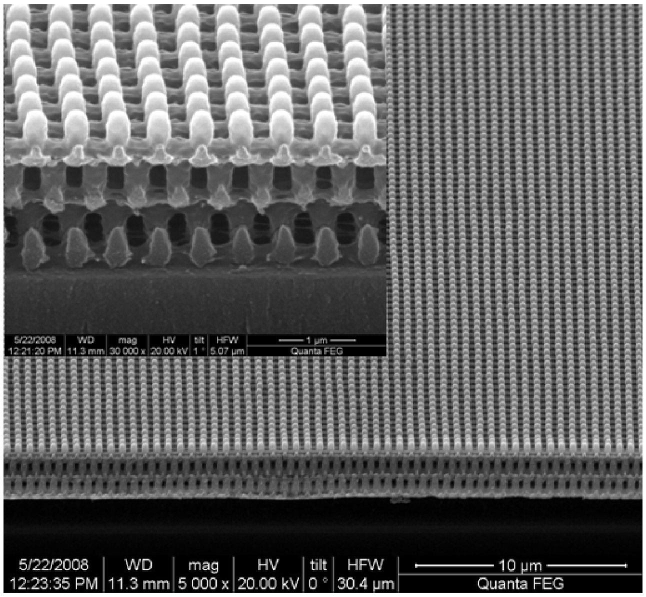

Figure 1: Example of 3D nanostructure made by the PnP method with a periodic square array.

Three-dimensional (3D) nanostructures are vital for emerging technologies such as photonics, sensors, fuel cells, catalyst supports, and data storage. Conventional fabrication (repeated cycles of standard photolithography with selective material removal) is costly, time-consuming, and produces limited geometries. Unconventional methods (colloidal self assembly, template-controlled growth, and direct-write or holographic lithography) have uncertain yields, poor defect control, small areas, and/or complicated and costly optical equipment. The Proximity-field nanoPatterning (PnP) method overcomes these limitations by generating complex 3D nanostructures using a simple optic and one lithographic exposure and development cycle. The optic is an elastomeric "phase mask" patterned in 3D dimensions roughly equal to the exposure wavelength. The phase mask is laid directly onto a spincast photopolymer and the light intensity pattern exposes the photopolymer in certain regions. Light exposure through the mask generates a complex 3D light intensity distribution due to diffraction and the Talbot effect. The exposed photopolymer is baked and developed, producing a 3D network of nanostructures with a single lithography cycle (Figure 1).

The PnP process has been transferred to the Sandia microfabrication facility, and scaled-up to produce 3D nanostructures across a full 6-inch wafer, thus making potential integration with microelectronics and microsystems possible. Modification of the photopolymer with solid reactive diluents has led to reduced structural shrinkage (due to chemical cross-linking that occurs upon post-exposure baking); while modification with conjugated organic dyes has led to the use of wavelengths outside the normal range (>500 nm). The 3D polymer nanostructures are fairly robust, but lack the materials characteristics desired for photonic applications. To alleviate this problem, a graded temperature approach was developed for atomic layer deposition to coat the 3D

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structures with dielectrics (Al_2O_3, ZnO, TiO_2) and metals (Pt), thus modifying the chemical, surface, and optical properties.

To predict the phase mask required to generate a specific desired nanostructure, a Finite Difference Time Domain (FDTD) modeling code was developed. The integrated tool starts with the desired device geometry and an initial guess of the PnP mask parameters. It then simulates the interference pattern and filters to reveal the expected photoresist burn image. Finally, it evaluates against the desired device. An integrated optimizer makes improvements to the mask parameters and cycles the simulation again. Using a silicon-inversion method to infiltrate PnP structures, a photonic crystal with a bandgap in the near infrared (900-1200 nm) has been fabricated in collaboration with the University of Illinois, Urbana-Champaign.

Aperiodic 3D nanostructures with Penrose quasicrystal patterns have been fabricated. Quasicrystals (high short-term order and non-repetitive long-term order) are applicable for photonics and electronics as they may possess a complete bandgap. An scanning electron microscope (SEM) image of the quasicrystal-patterned photopolymer, and the FDTD simulations are shown in Figure 2. Pattern recognition software was used to make comparisons of the modeled structures to confocal images of the exposed photopolymer (green insets) and 3D nanostructures, indicating a high level of accuracy (match >80%).

The PnP fabrication method can produce 3D nanostructures over large areas (mm^2) using a simple optic and a single cycle of lithography. Creation of an accurate and predictive model allows for true design of the periodic or aperiodic 3D nanostructures having the desired optical, physical, and structural properties. Surface modification and thin film deposition onto the 3D nanostructures allows for modification of the material and chemical properties of the structures. The flexibility, ease, and cost-effectiveness of the PnP method enables fabrication of 3D nanostructures on soft or curved surfaces, creation of nanocomposite and smart materials, manufacture of structures with high surface area for chemical sensors or chemical storage, and production of nano-scale patterned surfaces/structures for studies of cell growth mechanisms and controlled-release drug delivery.

References

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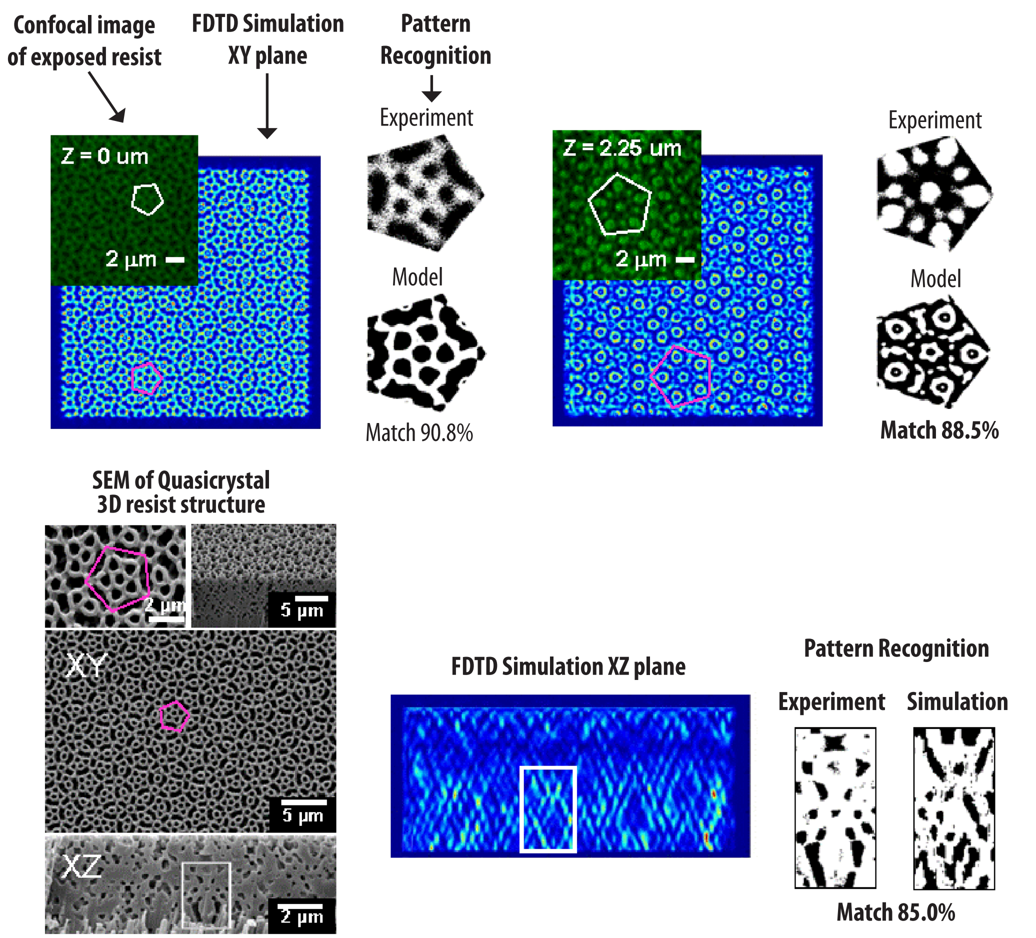

Figure 2: Comparison of SEM images (lower left) of a Penrose quasicrystal photoresist structure to FDTD-modeled resist structure in the rotational X-Y plane (blue upper left) and translational X-Z plane (blue, lower right), showing retention of 5-fold rotational symmetry in XY, and an absence of symmetry in XZ, characteristic of a quasicrystal. Also shown is a comparison to optical image (green) of exposed (but not developed) photoresist at different distances Z down from the surface. Quantitative comparison by pattern recognition methods are shown (black/white) to the right of the modeled images.